



Effects of floor impact noise on psychophysiological responses



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ABSTRACT

The present study analysed the effects of floor impact noise on humans using both psychological and physiological methods. Floor impact noises caused by a standard impact source (i.e. impact ball) and five real impact sources (e.g., human footsteps and dropped objects) were recorded as sound stimuli. During the laboratory experiments, two factors that impact psychophysiological responses were considered: (1) types of impact sources (standard or real sources) and (2) the levels of floor impact noise ranging from 31.5 to 63 dBA in terms of A-weighted maximum sound pressure level (L_{AFmax}). Twenty-one normal-hearing subjects were then asked to judge the noticeability and annoyance caused by the floor impact noises. Meanwhile, the subjects' physiological responses (heart rate: HR, electrodermal activity: EDA, and respiration rate: RR) were monitored throughout the experiments. Noise annoyance and noticeability increased with increases in noise levels, the impact ball resulted in higher noticeability and annoyance ratings than real sources. All physiological measures varied significantly with noise exposure; HR decreased, whereas EDA and RR increased. The results show that the physiological responses were not affected by the type of noise source. In addition, the noise level was found to be significantly related to EDA and RR changes, whereas the relationship between the noise level and HR was not found to be significant.

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1. Introduction

Several researchers have found non-auditory health effects of noise on people in laboratory and empirical studies [1,2]. Most research has attempted to analyse long-term health consequences of transportation noise such as aircraft or road traffic noise. Knipschild [3] argued that aircraft noise exposure is correlated with medical treatment for heart trouble and hypertension, higher use of cardiovascular drugs, and elevated blood pressure. Chronic exposure to aircraft or traffic noise increases physiological stress levels which can be measured through blood pressure or overnight epinephrine and norepinephrine [4,5]. Moreover, exposure to high traffic noise over long-term was reported to be correlated with the risk of coronary heart disease mortality [6]. Questionnaire survey studies also established a link between road traffic and aircraft noise and cardiovascular problems [7,8].

There is little evidence of health problems from noise in dwellings, although people spend most of their time in or around

their home. In addition, questionnaire surveys or interviews are used more frequently than epidemiological methodology. Guite et al. [9] identified associations between dissatisfaction with the noise from neighbours and mental health risks. Another study using a questionnaire survey reported that people who perceived neighbour noise as a severe annoyance experienced higher health risks including cardiovascular disease [10]. Hongisto et al. [11] recently found that various neighbour noises had adverse effects on sleep quality; particularly, they reported that footstep noise was found to be one of the most disturbing impact noises from neighbours. More specifically, recent studies [12,13] focused on floor impact noise mainly produced by a neighbour's footsteps. Park et al. [13] proposed a link between noise perception (i.e. annoyance and disturbance) and noise reaction in a conceptual model based on semi-structured interviews. In particular, according to their model, annoyance induced by floor impact noise has a reciprocal relationship with mental or physical health complaints. This association was validated by a questionnaire survey, later indicating statistically significant relationships between disturbance, annoyance, and health complaints [12]. However, epidemiological evidence was not established to confirm any relationship between dwelling noise and health problems.

The sound pressure level has been identified as a crucial factor

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affecting health problems. Chronic exposure to continuous noise at levels of at least 85 dBA was found to lead to higher blood pressure than individuals not exposed to noise [14]. It was also found that ambient traffic noise above 60 dBA had an impact on children's blood pressure and heart rate [15]. More recently, Babisch et al. [8] highlighted a significant association between aircraft noise and hypertension, which was stronger in more irritated people. Basner et al. [16] found a positive relationship between increasing noise levels and the risk of hypertension, strokes, and ischaemic heart diseases including myocardial infarction. Based on the relationships between noise levels and health issues, the World Health Organisation (WHO) proposed guidelines on noise levels in built environments to avoid damaging health effects [17]. The most frequently used approach to the study of the perception of noise is the use of questionnaires. However, self-reporting measures have some disadvantages; for example, some people may be less sensitive to small changes in stimuli than others and they may also tend to answer in socially desirable ways or in such a way that they would support the researcher's hypothesis. In contrast, physiological measurements are not controlled by the subjects but are triggered by the body, so that they can be regarded as objective measures. Therefore, the use of physiological measurements, in addition to questionnaires, would be beneficial to the study of the effects of noise on human and a number of studies have investigated the effects of noise on human using physiological measurements [18–21]. Despite a number of studies that reported the impact of noise levels on people's health, none have dealt with noise inside dwellings from neighbours, and in particular, floor impact noise. Therefore, it is necessary to explore the physiological responses to floor impact noise by measuring people's physiological data. The physiological measurements in conjunction with subjective ratings could provide further scientific evidence of floor impact noise on people.

Most studies on floor impact noise have used standard impact sources to create noise stimuli (e.g., tapping machine and impact ball). In particular, an impact ball has been used frequently in laboratory experiments [22,23] based on the physical similarities of an impact ball and humans. It was also reported that subjective perceptions of the impact ball are more similar to humans than other standard impact sources such as bang machine [23]. However, it remains unclear whether the physiological responses to a standard impact source are similar to those created by real sources.

This study aims to examine the psychophysiological responses to floor impact noise through laboratory experiments using three simple physiological measures (heart rate, electrodermal activity, and respiration rate). The experiments were used to examine the relationships between noise levels, source types, and psychophysiological responses, as well as to investigate differences in psychophysiological responses between a standard impact source and real sources.

2. Methods

2.1. Noise stimuli

Noise recordings were conducted in a test building which was designed to simulate the living rooms of residential buildings in Korea. Background noise level inside the test building was approximately 25 dBA. The floor layer of the building consisted of a 210 mm thick concrete slab, a 30 mm thick resilient material, a 40 mm thick lightweight concrete, and 40 mm thick mortar. All the room were furnished and wooden flooring was installed as a finishing material. The rooms were rectangular (4.5 m × 3.5 m) and the volume was around 38 m³. Noise stimuli were recorded binaurally through a head and torso simulator (Brüel & Kjær Type

4100). The head and torso simulator was positioned on the sofa of the receiving room and impact sources were dropped near the centre of the source room floor. Diotic stimuli were made using only the left channel signals of the binaural recordings, and were then presented to the subjects in the laboratory experiment to avoid the effects of spatial characteristics on perception [24]. The whole sound reproduction system was validated by comparing reproduced sounds with recorded sounds. The reproduced sounds were recorded at the point of the subject's ear using a head and torso simulator in an audiometric booth. The frequency response of the reproduced sound was almost identical to the recorded sound in the test building within 3 dB (octave band levels, 63–2000 Hz). However, a minor difference was found at 31.5 Hz because the frequency response of the loudspeaker was not flat below 50 Hz.

A total of six different noise sources were used to represent a majority of the impact noises in apartment buildings [25]. Five real sources were used with a standard heavyweight impact source (i.e. impact ball) adopted in ISO 10140-5:2010 Annex F [26]. The real sources were classified into two groups based on their physical characteristics; 1) heavyweight impact sources and 2) lightweight impact sources. The heavyweight impact sources included human footsteps, such as an adult walking barefoot, a child running and jumping barefoot, while lightweight impact sources were the dropping of a toy (0.5 kg) and the scraping of a chair. A male adult subject with a weight of 70.1 kg and a height of 170.6 cm and a seven years old child with a weight of 24.1 kg were chosen as general walkers. The dropping height of the impact ball and the toy was 1 m. The frequency characteristics of the stimuli are presented in Fig. 1. All of the stimuli have similar frequency characteristics with dominant sound pressure levels at low frequencies, especially at 63 Hz and 125 Hz. Temporal features of the stimuli were also analysed in terms of L_{10} , L_{50} and L_{90} and A-weighted equivalent sound pressure level (L_{Aeq}) and A-weighted maximum sound pressure level (L_{AFmax}), which was calculated using the Fast time constant. L_{10} , L_{50} and L_{90} describe the level exceeded for 10, 50, and 90% of the measuring period. As listed in Table 1, the sound climate ($L_{10} - L_{90}$) values for all noises were greater than 10 dBA, while the

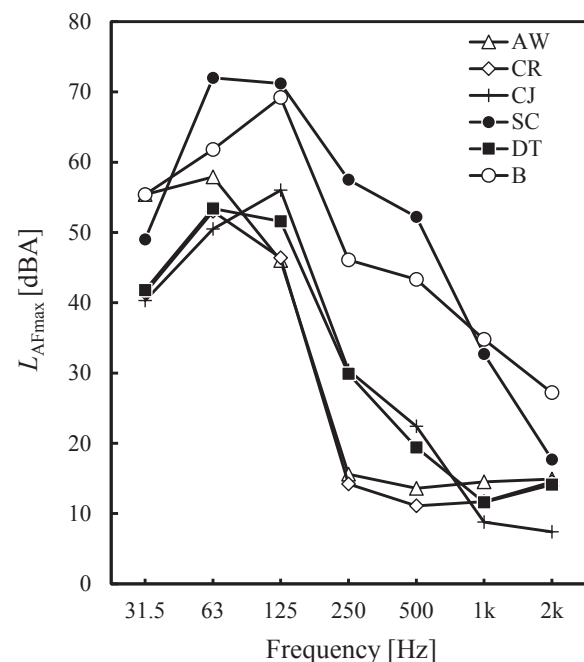


Fig. 1. Frequency characteristics of noise stimuli (AW: adult walking, CR: child running, CJ: child jumping, SC: scraping of a chair, DT: dropping of a toy, and B: impact ball).

Table 3
Outline of the laboratory experiment.

Sessions		1	2	3	4	5
Range of L_{AFmax} [dBA]		31.5 ~ 63.0	31.5 ~ 52.5	31.5 ~ 42.0	31.5 ~ 63.0	35.0 ~ 63.0
Noise stimuli	Type	Real	Real	Real	Standard	Real/standard
	Number	11	10	10	10	33
	Source*	AW	AW	AW	B	AW
		CR	CR	CR		CR
		CJ	CJ	CJ		CJ
		SC	SC	DT		SC
		DT	DT			DT
						B
L_{AE} of the session [dBA]		49.7	43.1	38.8	46.8	52.8
Duration of the session [min]		16.6	15.3	15.3	15.3	7.3
Measurements	Physiological response	HR, EDA, RR	HR, EDA, RR	HR, EDA, RR	HR, EDA, RR	-
	Psychological response	Noticeability / Annoyance of the session	Noticeability / Annoyance of the session	Noticeability / Annoyance of the session	Noticeability / Annoyance of the session	Annoyance of each stimulus

*AW: adult walking, CR: child running, CJ: child jumping, SC: scraping of a chair, DT: dropping of a toy, and B: impact ball

2.3. Measurements of psychophysiological responses

2.3.1. Psychological responses

It has been reported that the perception of noise is determined by short notice-events [28–30]. Therefore, in the present study, the psychological responses to floor impact noise were assessed in terms of noticeability and annoyance. As shown in Table 3, the noticeability of noise events was evaluated in Sessions 1–4, and the subjects were requested to press a response button whenever they heard a floor impact noise during the experiment. The subjects were also asked to rate their annoyance at the noise exposure using an 11-point scale (0 = “Not at all” to 10 = “Extremely”) at the end of Sessions 1–4. Annoyance generated by short-term noise exposure was evaluated in Session 5. In contrast to Sessions 1–4, the subjects evaluated the noise annoyance of each noise stimulus using a magnitude estimation technique. A reference noise with 42 dBA was presented to the subjects before they were exposed to each noise stimulus. They then rated the noise annoyance of the stimulus on the basis that annoyance caused by the reference noise was rated as 100. A training session for the magnitude estimation was used to help subjects become acquainted with this method.

2.3.2. Physiological responses

In the current study, three simple physiological measures were used: 1) heart rate (HR) expressed in beats per minute (BPM), 2) electrodermal activity (EDA) expressed in micro Siemens (μS), and 3) respiration rate (RR) expressed in beats per minute (BPM). All of the physiological responses were recorded on a laptop computer using a MP 150 WSW digital acquisition system (BIOPAC Systems) and were analysed using AcqKnowledge 4.4 (BIOPAC Systems). Two wireless amplifiers were placed under the desk where the subjects were seated. These amplifiers received all of the data from the recording units via the operation of a Bluetooth transmitting mode. The HR was gathered from the raw data of electrocardiographs (ECG), while the ECG was measured through electrodes attached to each subject's right wrist and both ankles. The EDA was measured using electrodes attached to the subjects' index finger and the middle finger of the right hand. The RR was computed from the raw

respiration data, which was measured through a respiration transducer belt worn around the chest. The respiration transducer belt records respiration data by measuring the changes in thoracic circumference that occur when an individual breathes.

It is known that there is a delay in the onset of stimulus-evoked physiological activity [31]. As the present study only focuses on analysing the response changes following such delays, the physiological data in noise exposure was collected for the last 18 s, excluding the first 5 s immediately after each stimulus delivery [32,33]. In addition, 50 s was designated before each noise stimulus as a baseline for comparison with the next noise stimulus. The subject's responses varied during baseline and noise exposure; therefore, the percentage change (%) was calculated to adjust all the different values [34]. The percentage change was defined as the percentage of change from the baseline to noise exposure.

2.4. Procedure

The subjects were asked to refrain from staying up all night or drinking alcohol before bedtime on the day before the experiment, and to avoid consuming caffeinated drinks on the day of the experiment. The experiments were conducted in an audiometric booth where the background noise level was set at approximately 25 dBA. To ensure precise measurements, all the electrodes were initially attached to the subject's body (right wrist, two fingers of the right hand, and both ankles) to make sure that the gel on each electrode was fully absorbed into the skin before the experiment commenced. The subjects were asked to sit facing two loudspeakers in front of them. A training session was carried out before the sessions began. The training session was 3 min long and consisted of noises produced by both real and standard impact sources. The subjects attended the five sessions on two different dates and the sessions were random. Given that resting and reading has a strong correlation with perceiving noise annoyance [35], the subjects were asked to read an e-book on a tablet placed in front of them and asked to imagine that they were resting in their own home.

2.5. Subjects

Twenty-one subjects (8 males and 13 females) aged between 18 and 42 (mean = 29.5, standard deviation = 6.6) took part in the experiment. None of the subjects reported hearing disabilities. Seven subjects were married and six of them had a child or several children. Of these subjects, 13 reported that they had experienced being exposed to noises from their upstairs neighbours or were experiencing issues with noise in their current dwelling.

2.6. Statistical analysis

Statistical analyses were performed using SPSS for Windows (version 22.0, SPSS Inc. Chicago, IL). Differences in the mean values were tested with the Wilcoxon signed-rank test to estimate the significance of the differences in the psychophysiological responses between real and standard impact sources. Repeated measures analysis of variance (ANOVA) was also used to investigate the effects of noise level and source type on the physiological responses. Greenhouse–Geisser adjusted degrees of freedom were used for tests of within-subject effects. In this study, p values less than 5% ($p < 0.05$) were considered statistically significant.

3. Results

3.1. Psychological responses

Fig. 2 shows the noticeability of floor impact sounds as a function of L_{AFmax} across the different sources. For both noise sources, the noticeability increased as the sound pressure level increased. Two regression lines show the difference between the standard impact source and real impact source. The solid and dotted lines represent the noticeability of the standard source and the real sources (AW, CR, CJ, SC, and DT), respectively. Some results of the real sources are invisible because they overlap with those of the standard impact source. For instance, the ratings of DT overlap with B at 42 dBA, while CJ and DT also overlap with B at 45.5 dBA. The correlation between noticeability and L_{AFmax} was found to be statistically significant ($r = 0.62$, $p < 0.01$ for whole stimuli, $r = 0.64$, $p < 0.01$ for standard source, and $r = 0.61$, $p < 0.01$ for real sources). Around 60% of the subjects noticed the noises at 38.5 dBA and the noticeability reached 100% when the levels were above 49 dBA. Differences between the two impact sources were identified between 35 and 45.5 dBA, and the differences gradually increased as the noise level increased. However, statistically significant

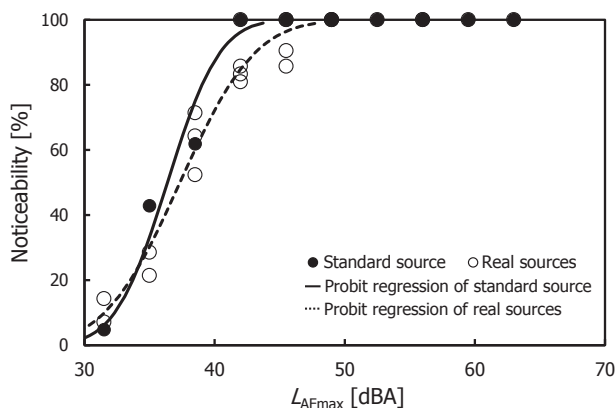
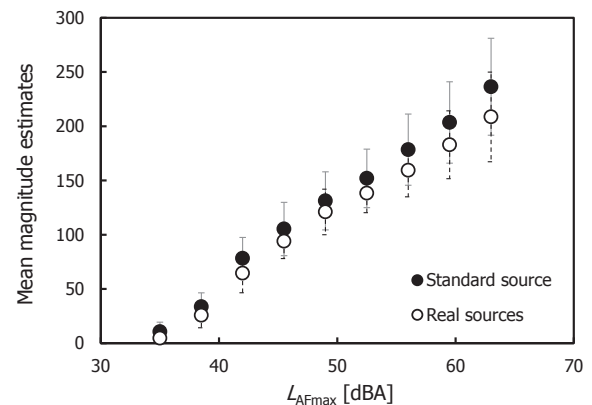


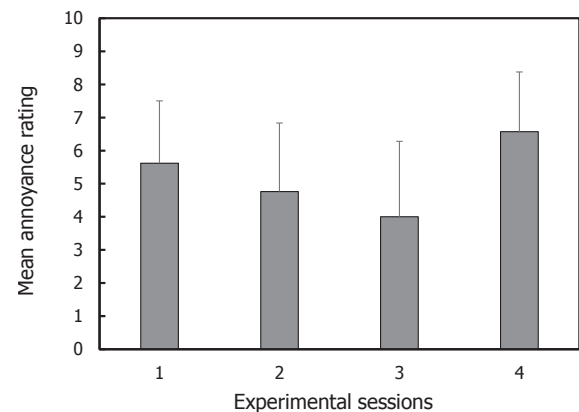
Fig. 2. Noticeability ratings for floor impact noise (●: standard impact source and ○: real impact sources) as a function of L_{AFmax} . Probit regression curves for standard and real impact sources are also presented.

differences between the sources were found at two levels (at 42.0 dBA, $p < 0.01$ and at 49 dBA, $p < 0.05$). It was found that the noticeability of the real impact sources also varied at the same levels according to the source type. For example, for noises at 38.5 dBA, the noticeability ranged from 52.4% to 71.4%. This variation may be the result of differences in temporal and spectral characteristics of the noises.

Fig. 3(a) shows the mean magnitude estimates of noise annoyance for each noise stimulus obtained from Session 5 using magnitude estimation, while Fig. 3(b) represents the mean annoyance ratings from Sessions 1–4. As shown in Fig. 3(a), the mean magnitude estimates of noise annoyance increased as the noise level increased for both standard and real sources. It was also observed that standard deviations also increased along with increase of noise level for both sources. The mean magnitude estimates of the standard impact source were consistently higher than those of the real impact sources and the statistical analysis confirms that the differences between the two sources were statistically significant at all levels. The correlation coefficients between mean magnitude estimates (annoyance ratings) and L_{AFmax} were greater than 0.9 for both sources ($r = 0.95$, $p < 0.01$ for whole stimuli, $r = 0.93$, $p < 0.01$ for standard source and $r = 0.95$, $p < 0.01$ for real sources). A correlation analysis also highlighted that the annoyance ratings of each stimulus were highly correlated with noticeability for both sources ($r = 0.43$, $p < 0.01$ for standard source and $r = 0.47$, $p < 0.01$ for real sources).



(a)



(b)

Fig. 3. Mean magnitude estimates of noise annoyance for each noise stimulus (a) and mean annoyance ratings of Sessions 1–4 (b) with error bars indicating standard deviation.

As shown in Fig. 3(b), the mean annoyance ratings of each session varied slightly across the sessions. The Wilcoxon signed-rank tests revealed that the mean annoyance ratings of Sessions 1–4 were all significantly different ($p < 0.01$). Session 3 with the real impact sources recorded the lowest noise annoyance rating (mean = 4.0, standard deviation = 2.3) due to the lowest L_{AE} . The highest annoyance rating (mean = 6.6, standard deviation = 1.8) was recorded in Session 4 with the standard impact source. The rating of Session 1 with the highest L_{AE} was slightly lower than Session 4, indicating that the standard impact source resulted in greater annoyance than the real sources. This implies that noise annoyance ratings were affected by the source type as well as the noise exposure level.

3.2. Physiological responses

The results of the psychological assessments demonstrate that the subjects hardly noticed the noise and reported very low annoyance ratings while noise levels remained below 38.5 dBA. Thus, the noise stimuli at 31.5 and 35.0 dBA were excluded from analyses of the subjects' physiological responses. Changes in HR, EDA, and RR were averaged for Sessions 1–4 and the mean changes were then presented for the standard and real sources in Fig. 4. The mean changes are listed in Table 4 with medians and standard deviations. The mean HR decreased by more than 1% for both sources and the difference between the baseline and the noise exposure was statistically significant ($p < 0.05$). HR response to the standard source decreased slightly more than that of the real sources but there was no significant difference between the sources. EDA increased significantly due to noise exposure ($p < 0.05$). The mean EDA changes were more than 2% for the standard source and 1% for the real sources; the standard source resulted in a higher increase than the real sources but the difference between the two types of source was not statistically significant. Similarly, significant RR increases (more than 3% for both sources) were recorded when subjects listened to floor impact sounds ($p < 0.05$). The RR change of standard source was higher than that of real sources which can be interpreted as meaning that the subjects were more sensitive to the standard impact source; however, the two changes were not statistically significant.

Fig. 5 shows the mean changes of HR, EDA, and RR as a function of L_{AFmax} . Open circles indicate the results from real sources and filled circles represent the responses to the standard impact source. The mean changes are also summarised in Table 5 with medians and standard deviations. Repeated measures of ANOVA was used to estimate the significance of differences in physiological response changes across different source (standard or real sources) and noise levels (L_{AFmax}). Source types had no significant main effect on any of the physiological responses. However, the main effects from noise

level were on EDA [$F(4.348,86.953) = 4.251$, ($p < 0.01$)] and RR [$F(4.797,95.944) = 4.748$, ($p < 0.01$)]. The interaction between source type and noise level had no significant impact on HR and EDA but influenced RR significantly [$F(4.772,95.439) = 3.715$, ($p < 0.01$)].

The findings of the correlation analysis show that, for the standard impact source, EDA and RR were influenced by L_{AFmax} ($r = 0.21$, $p < 0.01$ for EDA and $r = 0.31$, $p < 0.01$ for RR). For the real sources, EDA was correlated with L_{AFmax} ($r = 0.14$, $p < 0.01$); however, the relationship between HR and L_{AFmax} was not significant. Additional analysis was conducted to investigate whether the physiological response changes were influenced by psychological responses. As summarised in Table 6, noticeability for the standard impact source had impacts on EDA and RR ($r = 0.17$, $p < 0.05$ for EDA and $r = 0.41$, $p < 0.01$ for RR) and annoyance also correlated with EDA and RR ($r = 0.23$, $p < 0.01$ for EDA and $r = 0.17$, $p < 0.05$ for RR). In addition, annoyance to the real sources were correlated with EDA ($r = 0.13$, $p < 0.01$).

4. Discussion

4.1. Psychological evaluations of the floor impact sounds

Previous research [28–30] has reported a strong relationship between the noticeability and sound pressure levels of outdoor noises. These studies have also suggested that noise annoyance ratings can be explained by noticeability or detectability. The present study expanded their findings to indoor dwelling noises that are impulsive and transient. In this study, noticeability of floor impact noise was influenced by noise level and noise annoyance ratings were highly correlated with noticeability. This indicates that floor impact noise, when heard in residential buildings, may have a significant impact on residents' subjective judgements.

The impact ball was found to have a similar physical characteristic to humans in terms of mechanical impedance and impact force [36]. The subjective impression of the impact ball sound was also similar to a human-made sound [23]. Based on these findings, the impact ball was introduced as a standard impact source in international standard to mimic human footsteps (ISO 10140-5:2010) [26]. However, the findings of the present study show that psychological responses to impact ball sounds differed significantly compared to sounds produced by real sources in terms of both noticeability and annoyance.

4.2. Changes in physiological responses due to noise exposure

Park *et al.* [13] previously developed a model suggesting the relationships between noise exposure, annoyance, and health complaints. Among them, the relationship between annoyance and

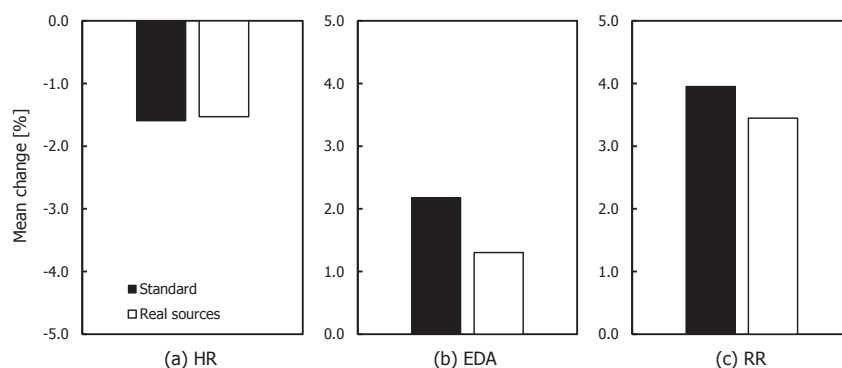


Fig. 4. Mean changes of physiological responses during Sessions 1–4: (a) HR, (b) EDA, and (c) RR.

Table 4

Mean changes of physiological responses for standard impact source and real impact sources. Values in second and third rows represent medians and standard deviations.

		HR	EDA	RR
Standard impact source	Mean changes (%)	−1.60	2.18	3.95
	Median (%)	−1.37	0.54	4.05
	Std. deviation	0.02	0.04	0.03
Real impact sources	Mean changes (%)	−1.53	1.30	3.45
	Median (%)	−1.28	0.13	3.12
	Std. deviation	0.03	0.04	0.04

health complaints was validated via a questionnaire survey [12]. The findings from the present study provided evidence to confirm this relationship in laboratory experiments. This study found that the annoyance ratings of the standard source were correlated with

EDA and RR and the annoyance of real sources were correlated with EDA. In addition, the present study revealed that noise level had key effects on the mean changes in EDA and RR. This implies that noise exposure might influence health problems as well as annoyance confirming the conclusion of a previous study [13] in which multiple relationships between noise exposure, perception, and health were suggested. An independent-samples T-test was used in order to assess whether there was any difference between the physiological responses of the subjects who had the past experience of being exposed to floor impact noise ($n = 13$) and those who had no past experience ($n = 8$). There was no significant difference between the HR and EDA of the two groups. However, there was a significant difference in the mean change of RR between those who had the past experience (mean = 3.7%, standard deviation = 0.04) and those who did not have any past experience (mean = 3.4%, standard deviation = 0.03); $t(734) = -3.20$, $p = 0.001$. This is in line with Park et al.'s [13] previous suggestion that having past experiences of noise exposure can affect health complaints. In addition, it was found that there was a significant difference in noticeability between those who had the past experience (mean = 77.3%, standard deviation = 0.42) and those who did not have any past experience (mean = 63.1%, standard deviation = 0.48); $t(619) = -4.40$, $p = 0.000$, whereas the differences in annoyance ratings between the groups were not significant.

Lang et al. [37] proposed a model indicating the relationship between physiological responses and arousal intensity. According to this model, people's physiological responses to the stimuli can be classified into three stages: pre-encounter, post-encounter, and circa-strike. Circa-strike is the final stage, which involves active defense and thus aims to eliminate reactions to secondary, probe stimuli [37]. Before presentation of the stimuli, physiological responses such as HR and EDA are almost calm in the pre-encounter stage, while HR decreases and EDA increases with exposure to arousal stimuli during the post-encounter stage. The changes of HR and EDA occur because people's attention is oriented to stimuli [37,38]. While high arousal stimuli are presented, EDA keeps increasing, but HR changes its direction upward. A number of studies have confirmed the changes in HR and EDA in the post-encounter and circa-strike stages through laboratory experiments. Bradley et al. [18] found that 6-s arousing and unpleasant sounds led to significant HR deceleration. Similarly, Hume et al. [19] reported deceleration in HR during the presentation of 8-s sound clips. On the other hand, several studies [20,21] using highly arousing noise stimuli reported HR accelerations indicating the circa-strike stage. Gomez et al. [20] used 30-s noise stimuli varying from 52.2 to 77.5 dBA, while Holand et al. [21] presented 0.15-s noise at 110 dBA to the subjects. Regarding the changes of EDA, Tajadura-Jiménez et al. [39] found that unpleasant and arousing sounds resulted in the largest EDA increases. Reinhardt et al. [40] also reported a significant increase in EDA resulting from 5-min long noise exposures ranging from 78 to 93 dBA. In addition, EDA increases evoked by noise stimuli were observed in recent soundscape studies [41,42]. In the present study, HR decreased but EDA

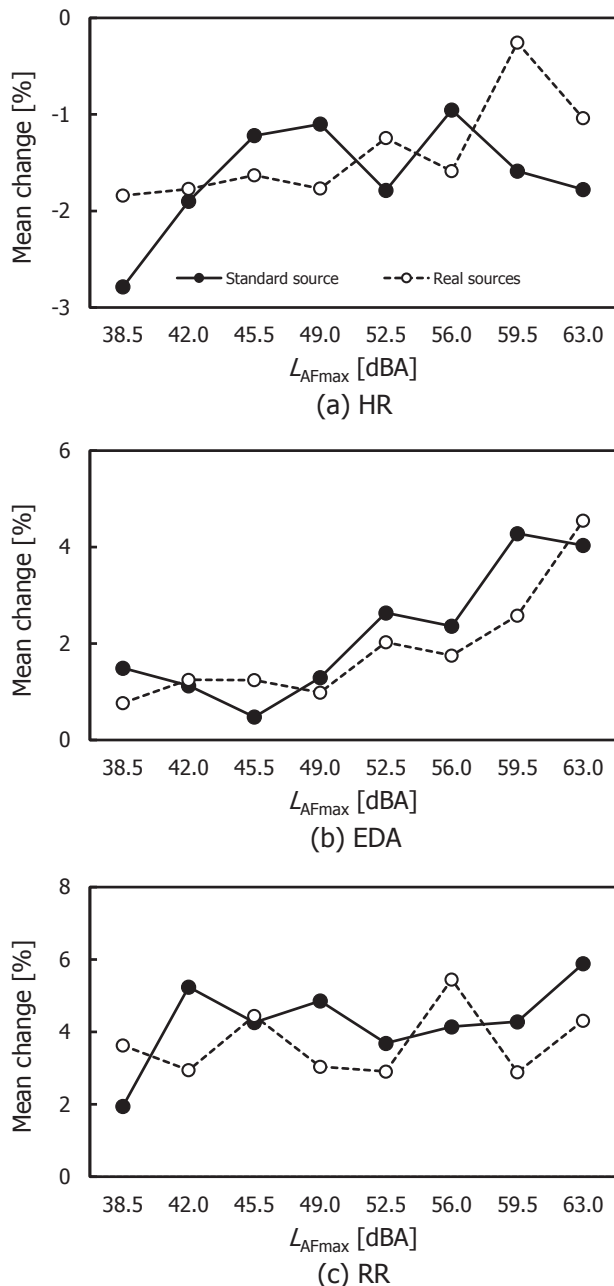


Fig. 5. Mean changes of physiological responses as a function of L_{AFmax} : (a) HR, (b) EDA, and (c) RR.

Table 5
Mean changes of physiological responses at each noise level for standard impact source and real impact sources. Values in second and third rows represent medians and standard deviations.

		L_{AFmax} [dBA]							
		38.5	42.0	45.5	49.0	52.5	56.0	59.5	63.0
a) Standard impact source									
HR	Mean changes (%)	−2.79	−1.90	−1.22	−1.10	−1.79	−0.95	−1.59	−1.78
	Median (%)	−2.90	−1.89	−0.41	−0.86	−1.93	−0.76	−0.91	−1.75
	Std. deviation	0.03	0.03	0.03	0.02	0.01	0.01	0.02	0.02
EDA	Mean changes (%)	1.49	1.13	0.48	1.29	2.64	2.36	4.28	4.04
	Median (%)	0.10	0.54	−0.73	0.45	1.15	0.54	4.19	3.24
	Std. deviation	0.05	0.02	0.03	0.03	0.05	0.05	0.02	0.04
RR	Mean changes (%)	1.94	5.24	4.26	4.85	3.68	4.14	4.28	5.89
	Median (%)	1.71	5.37	3.89	4.97	3.28	4.05	4.22	5.57
	Std. deviation	0.04	0.02	0.04	0.03	0.03	0.01	0.01	0.02
b) Real impact sources									
HR	Mean changes (%)	−1.84	−1.77	−1.63	−1.77	−1.25	−1.59	−0.26	−1.04
	Median (%)	−1.47	−1.46	−0.68	−1.52	−0.86	−1.40	−0.16	−0.39
	Std. deviation	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03
EDA	Mean changes (%)	0.77	1.25	1.24	0.99	2.03	1.75	2.58	4.55
	Median (%)	0.13	0.04	0.10	0.20	0.34	0.24	2.77	3.85
	Std. deviation	0.02	0.04	0.04	0.04	0.05	0.05	0.05	0.04
RR	Mean changes (%)	3.62	2.94	4.44	3.04	2.90	5.45	2.88	4.31
	Median (%)	3.65	2.28	4.43	2.55	2.70	5.57	2.33	4.69
	Std. deviation	0.03	0.04	0.04	0.04	0.02	0.03	0.03	0.03

increased due to noise exposure indicating that subjects were in a post-encounter stage rather than a circa-strike stage. This is because the noise levels presented in this study were not sufficient to lead to high arousal status and durations of noise exposure were quite short.

Our laboratory experiment also revealed that RR accelerated during noise exposure. This result is consistent with the findings of previous studies [19,20,43], in which experiences of arousal or emotions (e.g., anger and fear) lead to an increase of RR. Gomez et al. [20] found accelerated breathing with decreasing pleasantness using noises ranging from 52.2 to 76.7 dBA, while Gomez et al. [43] reported an association between arousal incurred by sounds and respiratory responses. Hume et al. [19] also found accelerated RR with man-made sound exposures [12,13].

4.3. Relationship between sound pressure level and physiological responses

A number of field and laboratory studies have addressed the associations between sound pressure levels and physiological responses. Several field studies have reported that physiological responses were influenced by the sound pressure levels of stimuli. Regecová et al. [15] found that children living in areas with high levels of traffic noise (>60 dBA) showed lower HR than those in

quiet areas, while Stansfeld [44] reported a positive correlation between sound pressure levels and EDA. Zahr et al. [45] also found significant respiratory changes in infants when sound pressure levels were reduced by wearing earmuffs. Moreover, Babisch et al. [8] identified significant relationships between transportation noise levels and hypertension. However, a recent laboratory study [19] came to the opposite conclusion; the sound pressure levels of 8 s stimuli were not correlated with physiological responses (heart rate, respiratory rate, and forehead electromyography level). The present study showed that sound pressure levels were correlated with EDA and RR, whereas the relationships between HR and noise levels were insignificant. The inconsistency between field and laboratory studies may be the result of different durations of noise exposure. Contrary to field studies dealing with longer noise exposure [8,15,45], Hume et al. [19] and the present study focused on short noise effects on physiological responses.

4.4. Future research needs

There are several points to be improved upon in the design of future psychophysiological studies of floor impact noise. First, as discussed in the previous section, different changes in HR have been found in different studies. As most of them used short noise stimuli (<30 s), further investigation using longer stimuli would be helpful for understanding long-term changes of physiological responses including HR. Second, noise sensitivity has a significant influence on the prevalence of noise annoyance [46,47]. In particular, Öhrström et al. [47] stated that noise annoyance is affected not just by general neurophysiological sensitivity but also subjectively reported noise sensitivity. Future studies could focus on potential physiological indices that can represent individual noise sensitivity ratings. Third, this study measured three simple physiological responses (HR, EDA, and RR); however, additional measurements of other physiological data (e.g., respiratory sinus arrhythmia: RSA) would also be beneficial to gain new or broader insights into the adverse effects of floor impact noise. Fourth, the loudspeakers could be located above the subjects to simulate the sound from an upper floor and a subwoofer could be used to reproduce low frequency sounds below 50 Hz.

Table 6
Correlation coefficients between the mean changes of physiological responses, annoyance, noticeability, and sound pressure level (L_{AFmax}) (** $p < 0.01$; * $p < 0.05$).

	Annoyance	Noticeability	L_{AFmax}
a) Standard impact source			
HR	0.13	−0.12	0.03
EDA	0.23**	0.17*	0.21**
RR	0.17*	0.41**	0.31**
b) Real impact sources			
HR	0.06	−0.03	0.02
EDA	0.13**	0.02	0.14**
RR	0.01	0.04	0.05

5. Conclusion

This study investigated subjects' psychological responses (noticeability and annoyance) and physiological responses (HR, EDA, and RR) to floor impact noises produced by both standard and real sources. The findings show that noticeability increased with higher sound pressure levels, and noise induced by the standard impact source led to higher noticeability than the real impact sources. Noise annoyance ratings also increased as sound pressure levels were increased. The annoyance ratings of the standard impact source were also greater than the real sources. The physiological responses to noise stimuli were calculated from the experiment. Deceleration in HR, increases in EDA and RR were identified during the noise exposure, demonstrating that the noise stimuli influenced the arousal status of the subjects. The physiological responses were not affected by the type of source (standard or real impact source), whereas the sound pressure level had a major impact on EDA and RR. In addition, annoyance and noticeability for real sources were correlated with EDA and RR, whereas psychological responses to the standard impact source showed no relationship with any physiological measure. Future research is required to further understand the long-term effects of floor impact noise on physiological responses by considering subjects' personal factors such as noise sensitivity.

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References

- [1] W. Passchier-Vermeer, W.F. Passchier, Noise exposure and public health, *Environ. Health Perspect.* 108 (2000) 123.
- [2] H.M.E. Miedema, C.G.M. Oudshoorn, Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals, *Environ. Health Perspect.* 109 (2001) 409–416.
- [3] P.V. Knipschild, Medical effects of aircraft noise: community cardiovascular survey, *Int. Arch. Occ. Env. Hea* 40 (1977) 185–190.
- [4] G.W. Evans, M. Bullinger, S. Hygge, Chronic noise exposure and physiological response: a prospective study of children living under environmental stress, *Psychol. Sci.* 9 (1998) 75–77.
- [5] Y. Aydin, M. Kaltenbach, Noise perception, heart rate and blood pressure in relation to aircraft noise in the vicinity of the Frankfurt airport, *Clin. Res. Cardiol.* 96 (2007) 347–358.
- [6] W.Q. Gan, H.W. Davies, M. Koehoorn, M. Brauer, Association of long-term exposure to community noise and traffic-related air pollution with coronary heart disease mortality, *Am. J. Epidemiol.* 175 (2012) 898–906.
- [7] A. Fyhri, G.M. Aasvang, Noise, sleep and poor health: modeling the relationship between road traffic noise and cardiovascular problems, *Sci. Total Environ.* 408 (2010) 4935–4942.
- [8] W. Babisch, G. Pershagen, J. Selander, D. Houthuijs, O. Breugelmans, E. Cadum, et al., Noise annoyance – a modifier of the association between noise level and cardiovascular health? *Sci. Total Environ.* 452 (2013) 50–57.
- [9] H. Guite, C. Clark, G. Ackrill, The impact of the physical and urban environment on mental well-being, *Public Health* 120 (2006) 1117–1126.
- [10] C. Maschke, H. Niemann, Health effects of annoyance induced by neighbour noise, *Noise Control Eng. J.* 55 (2007) 348–356.
- [11] V. Hongisto, M. Mäkilä, M. Suokas, Satisfaction with sound insulation in residential dwellings—the effect of wall construction, *Build. Environ.* 85 (2015) 309–320.
- [12] S.H. Park, P.J. Lee, K.S. Yang, K.W. Kim, Relationships between non-acoustic factors and subjective reactions to floor impact noise in apartment buildings, *J. Acoust. Soc. Am.* 139 (2016) 1158–1167.
- [13] S.H. Park, P.J. Lee, K.S. Yang, Perception and reaction to floor impact noise in apartment buildings: a qualitative approach, *Acta Acust. United Ac* 102 (2016) 902–911.
- [14] Y. Zhao, S. Zhang, S. Selvin, R.C. Spear, A dose response relation for noise induced hypertension, *Br. J. Industrial Med.* 48 (1991) 179–184.
- [15] V. Regecová, E. Kellerová, Effects of urban noise pollution on blood pressure and heart rate in preschool children, *J. Hypertens.* 13 (1995) 405–412.
- [16] M. Basner, W. Babisch, A. Davis, M. Brink, C. Clark, S. Janssen, et al., Auditory and non-auditory effects of noise on health, *Lancet* 383 (2014) 1325–1332.
- [17] B. Berglund, T. Lindvall, D.H. Schwela, Guidelines for Community Noise, World Health Organization, 1999.
- [18] M.M. Bradley, P.J. Lang, Affective reactions to acoustic stimuli, *Psychophysiology* 37 (2000) 204–215.
- [19] K. Hume, M. Ahtamad, Physiological responses to and subjective estimates of soundscape elements, *Appl. Acoust.* 74 (2013) 275–281.
- [20] P. Gomez, B. Danuser, Affective and physiological responses to environmental noises and music, *Int. J. Psychophysiol.* 53 (2004) 91–103.
- [21] S. Holand, A. Girard, D. Laude, C. Meyer-Bisch, J.-L. Elghozi, Effects of an auditory startle stimulus on blood pressure and heart rate in humans, *J. Hypertens.* 17 (1999) 1893–1897.
- [22] P.J. Lee, J.H. Kim, J.Y. Jeon, Psychoacoustical characteristics of impact ball sounds on concrete floors, *Acta Acust. United Ac* 95 (2009) 707–717.
- [23] J.Y. Jeon, P.J. Lee, S. Sato, Use of the standard rubber ball as an impact source with heavy-weight concrete floors, *J. Acoust. Soc. Am.* 126 (2009) 167–178.
- [24] J.Y. Jeon, P.J. Lee, J.H. Kim, S.Y. Yoo, Subjective evaluation of heavy-weight floor impact sounds in relation to spatial characteristics, *J. Acoust. Soc. Am.* 125 (2009) 2987–2994.
- [25] S.H. Park, P.J. Lee, B.K. Lee, Levels and sources of neighbour noise in heavy-weight residential buildings in Korea, *Appl. Acoust.* 120 (2017) 148–157.
- [26] ISO 10140-5, Acoustics – Laboratory Measurement of Sound Insulation of Building Elements, Part 5: Requirements for Test Facilities and Equipment, International Organization for Standardization, Geneva, Switzerland, 2010.
- [27] J. Little, J. Mabry, Sound duration and its effect on judged annoyance, *J. Sound. Vib.* 9 (1969) 247–262.
- [28] P.D. Schomer, L.R. Wagner, On the contribution of noticeability of environmental sounds to noise annoyance, *Noise Control Eng. J.* 44 (1996) 294–305.
- [29] S. Fidell, S. Tefeteller, R. Horonjeff, D.M. Green, Predicting annoyance from detectability of low-level sounds, *J. Acoust. Soc. Am.* 66 (1979) 1427–1434.
- [30] M. Sneddon, K. Pearsons, S. Fidell, Laboratory study of the noticeability and annoyance of low signal-to-noise ratio sounds, *Noise Control Eng. J.* 51 (2003) 300–305.
- [31] H.S. Friedman, C.E. Priebe, Estimating stimulus response latency, *J. Neurosci. Methods* 83 (1998) 185–194.
- [32] F.K. Graham, R.K. Clifton, Heart-rate change as a component of the orienting response, *Psychol. Bull.* 65 (5) (1966) 305–320.
- [33] M.E. Dawson, A.M. Schell, D.L. Filion, The electrodermal system, in: J.T. Cacioppo, L.G. Tassinari, G.G. Berntson (Eds.), *Handbook of Psychophysiology*, Cambridge University Press, USA, 2007, pp. 159–181.
- [34] L. Kaiser, Adjusting for baseline: change or percentage change? *Statistics Med.* 8 (1989) 1183–1190.
- [35] S. Abo-Qudais, H. Abu-Qdais, Perceptions and attitudes of individuals exposed to traffic noise in working places, *Build. Environ.* 40 (2005) 778–787.
- [36] J.Y. Jeon, J.K. Ryu, J.H. Jeong, H. Tachibana, Review of the impact ball in evaluating floor impact sound, *Acta Acust. United Ac* 92 (2006) 777–786.
- [37] P.J. Lang, M.M. Bradley, B.N. Cuthbert, Motivated attention: affect, activation, and action, in: P.J. Lang, R.F. Simons, M.T. Balaban (Eds.), *Attention and Orienting: Sensory and Motivational Processes*, Lawrence Erlbaum Associates, 1997, pp. 97–135.
- [38] W. Boucsein, *Electrodermal Activity*, Springer Science & Business Media, 2012.
- [39] A. Tajadura-Jiménez, P. Larsson, A. Våljamäe, D. Västfjäll, M. Kleiner, When room size matters: acoustic influences on emotional responses to sounds, *Emotion* 10 (2010) 416–422.
- [40] T. Reinhardt, C. Schmahl, S. Wüst, M. Bohus, Salivary cortisol, heart rate, electrodermal activity and subjective stress responses to the Mannheim Multicomponent Stress Test (MMST), *Psychiat Res.* 198 (2012) 106–111.
- [41] P. Lindborg, Physiological measures regress onto acoustic and perceptual features of soundscapes, *The 3rd International Conference on Music & Emotion, ICME3, Jyväskylä, Finland*, 2013.
- [42] O. Medvedev, D. Shepherd, M.J. Hautus, The restorative potential of soundscapes: a physiological investigation, *Appl. Acoust.* 96 (2015) 20–26.
- [43] P. Gomez, P. Zimmermann, S. Guttormsen-Schär, B. Danuser, Respiratory responses associated with affective processing of film stimuli, *Biol. Psychol.* 68 (2005) 223–235.
- [44] S.A. Stansfeld, Noise, noise sensitivity and psychiatric disorder: epidemiological and psychophysiological studies, *Psychol. Med. Monogr. Suppl.* 22 (1992) 1–44.
- [45] L.K. Zahr, J. de Traversay, Premature infant responses to noise reduction by earmuffs: effects on behavioral and physiologic measures, *J. Perinatology* 15 (1994) 448–455.
- [46] R.F.S. Job, Community response to noise – a review of factors influencing the relationship between noise exposure and reaction, *J. Acoust. Soc. Am.* 83 (1988) 991–1001.
- [47] E. Öhrström, M. Björkman, R. Rylander, Noise annoyance with regard to neurophysiological sensitivity, subjective noise sensitivity and personality variables, *Psychol. Med.* 18 (1988) 605–613.